

## CATALYTIC WALL-FLOW FILTER

This application is a divisional of U.S. Patent Application No. 09/807,571, filed July 23, 2001 (the entire disclosure of which is expressly  
5 incorporated by reference herein), which is the U.S. National Phase of International Application No. PCT/GB00/03064, filed August 14, 2000, which claims priority of British Patent Application No. 9919013.4, filed August 13, 1999.

This invention relates to a wall-flow filter, and in particular to a wall-flow filter including a catalyst.

10 Exhaust gases of a combustion engine contain a number of components linked with damaging health and the environment. One of these is the soot component. A way of controlling the amount of soot in the exhaust gas is to use a filter downstream from the exhaust manifold, the idea being to burn (oxidise) soot trapped on the filter, thereby regenerating the filter.

15 A known type of soot filter is the wall-flow filter. This filter can be made, for example, from a ceramic monolith including channels in a honeycomb arrangement. A typical embodiment has each channel plugged at one or other end thereof, and at the opposite end to the laterally and vertically adjacent channels.

When viewed from either end, the alternately plugged and open ends of the channels take on the appearance of a chessboard. The ceramic material from which the filter can be made has a pore size sufficient to allow gas permeability so that the pressure drop across the filter is relatively low, but which prevents the passage of soot. Thus  
5 soot is filtered from the exhaust gases.

EP-A-0341832 and corresponding case US-A-4,902,487 describes a process and treatment system for soot-containing exhaust gas, the gas also containing nitric oxide (NO), which process comprising passing the gas unfiltered over an oxidation catalyst to convert NO to nitrogen dioxide (NO<sub>2</sub>), collecting the soot  
10 on a downstream filter and combusting the collected soot continuously at under 400°C by reaction with the NO<sub>2</sub>; and there have been recent proposals to add further steps to that process and system, for example nitrogen oxides (NO<sub>x</sub>) removal steps (see EP-A-0758713). EP-A-0341832 and US-A-4,902,487 describe Johnson Matthey's Continuously Regenerating Trap (CRT™) technology and are incorporated herein by  
15 reference.

In the process described in EP-A-0341832 the oxidation step and the filter combustion step are carried out in two different honeycombs each in a separate shell or can or mounted within a single can. However, there are problems in adopting either embodiment. A problem with the former embodiment is that there can be  
20 limited space under-floor on a vehicle to mount each can. In the latter embodiment, a problem is that the construction of the can is complicated. If further downstream process steps are required these problems are exacerbated.

We have now found that these and other problems can be overcome or reduced by carrying out each of the treatment steps on a single wall-flow filter or single "brick". US-A-5,089,237 discloses a soot burn-off filter for an exhaust system of a combustion engine, which filter includes a porous ceramic honeycomb block having channels plugged alternately at the ends to define a flow path through the partition walls of the channels, the walls at the inlet end having a catalytic coating. We understand from this document that the filter is used in a discontinuous process in which soot is allowed to accumulate on the filter and is periodically burnt off by raising the temperature and ensuring that sufficient oxygen ( $O_2$ ) is available. Owing to the combustion of a substantial quantity of soot in a relatively small space, temperatures high enough to produce destructive effects on the filter are readily attained. To limit such effect the filter of US-A-5,089,237 provides a gas-tight region in the partition walls at the downstream end of the upstream channels. Although the catalytic coating is stated to lower the temperature at which soot combustion takes place, it evidently does not make the gas-tight region unnecessary.

According to one aspect, the invention provides a wall-flow filter for an exhaust system of a combustion engine, which filter comprises: a plurality of channels in honeycomb arrangement, wherein at least some of the channels are plugged at an upstream end and at least some of the channels not plugged at the upstream end are plugged at a downstream end; an oxidation catalyst on a substantially gas impermeable zone at an upstream end of the channels plugged at the downstream end; and a gas permeable filter zone downstream of the oxidation catalyst for trapping soot, characterised in that in an exhaust system the oxidation catalyst is capable of generating sufficient  $NO_2$  from NO to combust the trapped soot continuously at a temperature less than  $400^\circ C$ .

The term "continuously" means that collected soot is combusted in a continuous exhaust gas flow; it thus excludes (except in the event of malfunction) the combustion of a large amount of accumulated soot. It does, however, encompass relatively minor variations in the level of collected soot and in the gas composition in response to normal variations of engine operating conditions and to short-term injection of reductant or NOx specific reactants in order to remove NOx downstream of the filter.

For the avoidance of doubt, by "absorb" herein, we mean to hold a relevant species on a relevant surface of a body (otherwise "adsorb") and/or to hold a species below the surface of a body i.e. within the body.

Exhaust gases from a combustion engine also contain unburnt hydrocarbon (HC), carbon dioxide (CO<sub>2</sub>), carbon monoxide (CO), steam (H<sub>2</sub>O(g)) and nitrogen (N<sub>2</sub>). Its content of NOx comprises NO and NO<sub>2</sub>, the majority being NO. At least sufficient NOx should be present to provide, after the catalytic oxidation of NO to NO<sub>2</sub>, at least enough NO<sub>2</sub> to oxidise the collected soot as it is formed, or after a small accumulation of soot. As described in the above mentioned EP-A-0341832, and in PCT application no. GB00/02062, additional NOx may be supplied by e.g. injecting nitric acid or the product of local oxidation of ammonia (NH<sub>3</sub>) or an ammonia precursor, such as urea.

The filter of the present invention provides a gaseous flow path defined in part by the open ends of each channel plugged at the downstream end, and the pores of the gas permeable wall of the channel. Soot in the gaseous exhaust enters the channel, but cannot pass through the pores of the channel wall. Thus soot is

filtered from the gaseous exhaust by the pores of the filter. Furthermore, the gaseous exhaust is forced to flow over the entire zone supporting the oxidation catalyst, as the wall of the filter on which it is supported is substantially gas impermeable. This achieves the best possible yield of NO<sub>2</sub> from NO at a given  
5 temperature and also avoids caking the catalyst in soot.

Preferably, the arrangement of channels plugged at the upstream and downstream ends of the filter is such that each channel of the filter is plugged at one or other end thereof, and at the opposite end to the laterally and vertically adjacent channels, although other configurations can be used. For example, in an  
10 arrangement of striated appearance, a first longitudinal array of channels is plugged at one end, and the longitudinal arrays of channels either side of the first array are plugged at the opposite ends of the filter, and so on. The provision of a filter including at least some unplugged channels, thereby to act as a by-pass to the filter channels, is also within the ambit of the present invention. The unplugged channels  
15 can also be used to introduce a reactant required downstream of the wall-flow filter zone.

The channels are preferably square in cross-section but can be any other shape such as circular, rectangular, hexagonal or triangular.

Preferably, the oxidation catalyst, which is advantageously a  
20 compound including a platinum group metal (PGM), such as platinum (Pt) or palladium (Pd), blocks the filter pores in the gas impermeable zone, thereby making the zone substantially gas impermeable. Filter-grade materials for making the filter suitably have a mean pore diameter in the range  $0.4$  to  $20 \times 10^{-3}$  inch (1 to 50  $\mu\text{m}$ )

for gas treatments at about atmospheric pressure, but other values may be more appropriate for liquids or at higher or lower pressures. Although it is possible to manufacture a filter in which the filter material itself is gas impermeable or the pore size is graded so that the upstream part of channels plugged at the downstream end are gas impermeable but gas permeability increases towards the filter zone, we prefer that the filter material is of uniform pore size and that zones supporting the catalyst are rendered gas-impermeable by applying materials to them. When the filter is ceramic, it may be the product of shaping (e.g. by extrusion) and a composition containing sufficient fugitive material to leave, once removed e.g. by calcination, the required pores. The filter, whether ceramic or metal, may be the product of moulding and sintering a powder, possibly via foam. Whilst the filter material can be metal, we prefer it to be made of a ceramic material such as cordierite, alumina, mullite, silicon carbide, zirconia or sodium/zirconia/phosphate. The honeycomb has typically at least 50 cells per square inch ((cps)( 7.75 cm<sup>-2</sup>), possibly more, e.g. up to 800 cpsi (124 cm<sup>-2</sup>). Generally the range 100-600 cpsi (15.5-93 cm<sup>-2</sup>) is preferred, of which 200-400 cpsi (31-62 cm<sup>-2</sup>) is most preferred.

According to preferred embodiments, the downstream channels of the filter include a catalyst for a NO<sub>x</sub> absorber (or NO<sub>x</sub> trap) and optionally a NO<sub>x</sub> reduction catalyst or Selective Catalytic Reduction (SCR) catalyst downstream of the NO<sub>x</sub> absorber. The combination of CRT<sup>TM</sup> technology and the SCR of NO<sub>x</sub> with a nitrogen-containing compound, such as NH<sub>3</sub> or urea, is described in our WO 99/39809. In a further embodiment, the channels upstream of the oxidation catalyst can include a sulphur oxides (SO<sub>x</sub>) absorber (SO<sub>x</sub> trap). The upstream SO<sub>x</sub> absorber can be included in embodiments with or without the NO<sub>x</sub> absorber or NO<sub>x</sub> reduction catalyst or SCR catalyst. As with the zone including the oxidation catalyst, in

embodiments including one or more of the SO<sub>x</sub> absorber, NO<sub>x</sub> absorber or NO<sub>x</sub> reduction catalyst or SCR catalyst, the zones of each catalyst or absorber is substantially gas impermeable, and the gas impermeability is preferably provided by the catalyst or absorber or the catalyst or absorber support.

5                   The NO<sub>x</sub> absorber/trap comprises a compound including an alkali metal, an alkaline earth, rare earth metal or transition metal or a mixed oxide capable of forming nitrates and/or nitrites of adequate stability in non-reducing conditions and of evolving nitrogen oxides and/or nitrogen in reducing conditions, an oxidation catalyst, preferably Pt, and a reduction catalyst, preferably rhodium (Rh).  
10   Composite oxides of e.g. alkaline earth metal and copper can also be used, such as (adopting periodic table letter codes) Ba-Cu-O or MnO<sub>2</sub>-BaCuO<sub>2</sub>, possibly with added CeO<sub>2</sub>, or Y-Ba-Cu-O and Y-Sr-Co-O. The NO<sub>x</sub> reduction catalyst will generally include one or more PGM, but especially Pt, Pt/Rh, Pd/Rh or Pt/Pd/Rh. The SCR catalyst can be a copper-based material, Pt, a mixed oxide of vanadia (V<sub>2</sub>O<sub>5</sub>) and titania (TiO<sub>2</sub>) or  
15   a zeolite or mixtures of two or more thereof and is preferably V<sub>2</sub>O<sub>5</sub>/WO<sub>3</sub>/TiO<sub>2</sub>.  
Reference can be made to our WO 99/55446 and WO 99/39809 for further information. The SO<sub>x</sub> absorber can include an alkaline earth metal oxide or alkali metal oxide or mixtures of any two or more thereof. Reference can be made to our EP-A-0814242 for further details.

20                   In an exhaust system including an embodiment of the present invention including a NO<sub>x</sub> reduction catalyst or an SCR catalyst, the system can include means to inject reductant and/or NO<sub>x</sub>-specific reactant continuously or intermittently upstream of these catalysts. The oxidation catalyst of the invention can be in two parts, optimised respectively for oxidation of HC and CO and for

conversion of NO to NO<sub>2</sub>. In the embodiment including both the NO<sub>x</sub> absorber and reduction catalyst, they can be in distinct regions of the filter or associated, for example co-precipitated or co-impregnated or present as sandwiched layers or as relatively fine (e.g. 1-500 µm) particles or overlaid in different washcoats.

5                    Preferably, the or each catalyst or absorber is supported on a high-surface oxide support, preferably alumina (Al<sub>2</sub>O<sub>3</sub>), TiO<sub>2</sub> or zirconia (ZrO<sub>2</sub>), but the or each catalyst or absorber can be supported directly by the filter i.e. without additional high-surface oxide support.

                    Desirably, the catalyst(s) and, where present, absorber(s), whether  
10 supported on a high surface area oxide or directly by the filter, increases the local pressure-drop of the wall-flow filter by a factor of at least 2, and preferably up to 10. In one embodiment, the filter zone itself can be catalysed. A suitable catalyst is an oxidation catalyst to assist in combusting the soot, but more preferably the catalyst includes a base metal such as magnesium oxide (MgO) and most preferably the  
15 catalyst is a combination of lanthanum (La), caesium (Cs) and vanadium pentoxide (V<sub>2</sub>O<sub>5</sub>). Where the base metal is MgO, a preferred catalyst is Pt on MgO. If the surfaces of the pores of the filter zone are to carry a catalyst, the pore diameter may be in the upper fifth of the above mentioned range or even higher, but such coating should be thin enough to avoid the need for large pores that would weaken the filter  
20 structurally.

                    "Alkali metal" as defined herein includes potassium (K), sodium (Na), lithium (Li), rubidium (Rb) or Cs; "alkaline earth metal" includes barium (Ba),



calcium (Ca), strontium (Sr) or magnesium (Mg); and "rare earth metal" includes cerium (Ce), La or yttrium (Y) or other lanthanides.

The filter according to the invention can be packaged in any convenient way. Packaging materials commonly used in the art include a ceramic or steel wire mesh for wrapping and insulating the filter core; end plugs to prevent exhaust gas leaks through the wire mesh or to protect the mat; and steel for the shell or can. A suitable header can be used to provide the transition between the inlet and outlet pipes and the filter cross-section. Ports for the injection of additives or the introduction of sensor devices for on-board diagnostics can also be provided, where necessary.

The filter of the present invention can be made by methods known in the art, as exemplified by way of illustration only herebelow. In this aspect, the invention provides a method of making a filter according to the invention by stage-wise dipping in solutions and/or dispersions of precursors of the catalyst or absorber. In preferred features of this method, the method includes the steps of coating a wall of a channel of a wall-flow monolith with at least one material effective to decrease locally the gas permeability of the wall; and then applying to the coated wall at least one catalyst or absorber and optionally calcining the coated monolith.

However, we prefer to use the apparatus and method described in our WO 99/47260. To this end according to a further aspect, the invention provides a method of making a filter according to the invention comprising, in either order, the steps of: (i) locating a containment means on top of a wall-flow monolith having a plurality of channels in honeycomb arrangement, wherein at least some of the

channels are plugged at an upstream end and at least some of the channels not plugged at the upstream end are plugged at a downstream end; and (ii) dosing a pre-determined quantity of a liquid being a washcoat slurry or a solution of a catalyst or catalyst precursor, or a mixture of the two, into the containment means; and then  
5 (iii) by applying pressure or a vacuum, drawing said liquid component into at least a portion of the open wall-flow monolith channels, and retaining substantially all of the quantity within the channels.

In an alternative embodiment, the above method is applied to an unplugged monolith and the channels are plugged after the coatings have been  
10 applied. If one end of a channel is to be plugged, the method includes the step of removing coating applied to that end prior to plugging. Alternatively, the method includes the step of coating only the ends of channels which are predetermined to remain unplugged, i.e. the coating is not applied to an end of a channel which is to be plugged.

15 In a preferred feature, the method according to the invention comprises the step of applying a resist to a region where application of a washcoat or a solution or suspension of a catalyst or catalyst precursor or mixture thereof is to be delayed. The resist can be a wax or stearic acid, for example.

According to a further aspect of the invention, there is provided a  
20 combustion engine including an exhaust system having a filter according to the invention. Preferably, the combustion engine is a diesel engine.

In another aspect, the invention provides a vehicle fitted with a combustion engine, preferably a diesel engine, including an exhaust system having a filter according to the invention.

According to a further aspect of the invention there is provided the use  
5 of a filter according to the invention for treating exhaust gases from a combustion engine, preferably a diesel engine.

In a further aspect, the invention provides a process for removing by combustion soot deposited on a filter disposed in an exhaust system of a combustion engine wherein exhaust gas containing NO is initially passed without filtering over a n  
10 oxidation catalyst to convert NO in the exhaust gas to NO<sub>2</sub> prior to filtering to remove soot and wherein the exhaust gas containing NO<sub>2</sub> is then used to combust the soot trapped on the filter, the amount of NO converted to NO<sub>2</sub> being sufficient to enable combustion of soot trapped on the filter to proceed at a temperature less than 400°C, characterised in that the filter is a wall-flow filter, which filter comprises: a plurality  
15 of channels in honeycomb arrangement, wherein at least some of the channels are plugged at an upstream end and at least some of the channels not plugged at the upstream end are plugged at a downstream end; the oxidation catalyst is on a substantially gas impermeable zone at an upstream end of the channels plugged at the downstream end; and a gas permeable filter zone downstream of the oxidation  
20 catalyst for trapping soot.

In order that the invention may be more fully understood, reference will be made to the accompanying drawing which shows an elevated cross-sectional view of one embodiment of a filter according to the present invention.

Figure 1 shows three adjacent channels 4, 6, 8 of a cordierite honeycomb filter 10, having 200 cpsi ( $31 \text{ cm}^{-2}$ ) and, before use, pores of approximately  $10 \text{ }\mu\text{m}$  in diameter. Channel 6 is plugged at 12 at the upstream end of the filter 10 and the other two channels 4,8 are each plugged at 14 at the downstream end of the filter 10. Thus, gas entering channel 6 at the upstream end must pass through the walls of the channel 6 to reach the downstream end of the filter 10. Over a region or zone extending downstream of the opening to channel 6, the walls carry coating 16 comprising an  $\text{Al}_2\text{O}_3$  washcoat support and a metallic Pt oxidation catalyst. Coating 16 obstructs the pores of the filter walls. Over a region or zone extending upstream from the outlet to filter 10, channels 4 and 8 carry coatings 18, 20 comprising a NOx absorber composition including barium oxide (BaO) and a NOx reduction catalyst composition comprising Pt/Rh. In order to make the coatings 18, 20, the zone to be coated with coating 20 is first covered with a resist, such as wax or stearic acid, during application of coating 18. In this embodiment the regions of the cordierite filter 10 including coatings 16 and 18 are rendered gas impermeable by the presence of the coating. Between coatings 16 and 18, the walls of the channels 4, 6, 8 remain gas permeable and provide a filter zone 22.

Diesel exhaust gas entering the reactor undergoes oxidation of HC, CO and NO in presence of coating 16. Soot in the gas is collected on the walls of channels 4, 6, 8 at filter zone 22 and is combusted by  $\text{NO}_2$  derived from the oxidation of NO. The gas, containing soot combustion products, passes through the wall of the filter and contacts the NOx trap coating 18, which absorbs  $\text{NO}_2$ . When sufficient  $\text{NO}_2$  is stored (as the nitrate, for example), which can be ascertained by the on-board diagnostics of the vehicle, coating 18 can be regenerated with a rich pulse of gaseous exhaust i.e. gas including excess reductant such as HC. The rich/lean cycling can be

controlled using the vehicle's engine management system. The resulting NO<sub>x</sub>-rich gas contacts coating 20 including the NO<sub>x</sub> reduction catalyst, which effects oxidation of HC and CO and reduction of NO<sub>x</sub> to N<sub>2</sub>. Alternatively, where coating 20 is a SCR catalyst, NO<sub>x</sub>-specific reactant such as ammonia can be injected at an upstream end of the filter at a rate and temperature permitting unreacted ammonia to slip oxidation catalyst 16 and contact absorber 18, which it regenerates, and catalyst 20, over which it reduces NO<sub>x</sub> to N<sub>2</sub>.

In order that one method of manufacture of the filter according to the invention may be more fully understood, the following Example is provided by way of illustration only.

The substrate is a filter grade cordierite honeycomb monolith of square cross-section channels 30 mm in diameter and 150 mm long and having a mean pore diameter 10 µm in which half of the passages both ends of the monolith are plugged so that each channel of the monolith is plugged at one or other end thereof, and at the opposite end to the laterally and vertically adjacent channels.

One end of the monolith is labelled 'inlet' and is dipped 25 mm deep into an aqueous dispersion of hydrated Al<sub>2</sub>O<sub>3</sub>, then withdrawn, dried at 100°C and allowed to cool. The inlet end is then dipped to the same depth in an aqueous solution of 2% w/w platinum chloride. The monolith is dried as before.

The unlabelled end of the monolith is prepared by firstly dipping it to a depth of 25 mm in turn in an aqueous solution of sodium stearate and then drying the resulting monolith at 100°C. The resulting monolith is then dipped in aqueous hydrochloric acid and then water (two changes), to rinse off solubles. This procedure

produces an insoluble stearic acid layer as a resist, which excludes any materials applied in neutral or acidic solution. The resist-coated monolith is then dipped to a depth of 50 mm, into an aqueous solution of barium acetate and platinum chloride, and then dried. This dip applies these materials to an area upstream of the resist-coated area. Then the coated monolith is dipped in 5% w/w aqueous sodium hydroxide to a depth of 25 mm to dissolve the stearic acid resist. This step is repeated twice and is followed by two rinses with water. The coated monolith is then dried. The resulting monolith is then dipped to a depth of 25 mm in the  $\text{Al}_2\text{O}_3$  dispersion used at the inlet end, and described above. The coated monolith is then dried. Finally, to a depth of 25 mm in Pt/Rh solution. The coated monolith is then dried.

The resulting monolith is then calcined at  $500^\circ\text{C}$  for 1 hr to convert the metal salts to oxides or metals and to develop the surface area of the  $\text{Al}_2\text{O}_3$  to provide a filter according to the invention.